Remote Sensing of Water Quality in Prairie Lakes

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REMOTE SENSING OF WATER QUALITY IN PRAIRIE LAKES

BY

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A thesis submitted
in partial fulfillment of the requirements for the
degree Master of Science, Major in
Biology, South Dakota
State University

1975

ABSTRACT

The possibility of predicting prairie lake water quality using remote-sensing data during the 1974 open water season was investigated. Water quality samples were collected to coincide with satellite (LANDSAT-1) overpasses and low-altitude aircraft flights.

Twelve different remote-sensing estimates were taken from LANDSAT-1 imagery, low-altitude aerial photographs, ground-based radiometer, and ground-level photographs. These were correlated with prairie lake water transparency (secchi depth) and algae abundance (chlorophyll 'a' and total cell concentrations). For predictive purposes multiple regression analyses were performed using the three water quality parameters as dependent variables and the remote sensing parameters as independent variables. The correlations between the three water quality parameters and physical factors (rainfall, solar energy, wind velocity, water temperature, and water depth) and nutrient levels (nitrogen and phosphorus) were also investigated using multiple regression analyses.

All twelve remote-sensing estimates gave significant correlations with the water quality parameters measured. Film densities of ground photos taken directly over the water significantly correlated with the selected water parameters. Infrared films were most capable of detecting variations of chlorophyll 'a' and total algae while black and white film with a green filter best predicted water transparency for the aircraft data. Of the four spectral regions (bands) received by the LANDSAT-1 sensors, Band 4 (0.5 to 0.6 μm) best predicted chlorophyll 'a'

concentrations and Band 5 (0.6 to 0.7 μm) best predicted both total algae and water transparency.

All water quality parameters measured were significantly correlated with each other, with nutrient levels, and with some of the physical factors measured. Decreased water depth particularly was associated with higher nutrient levels, increased total algae and chlorophyll 'a', and decreased water transparency. Nitrate appeared to be the principal nutrient positively correlated with algal abundance.

Extensive ground-level photographic or radiometric measurements are impractical in many operational programs since the time involved on the ground would justify collection of actual water samples. Low altitude aerial photographs offer finer resolution of small areas but are more expensive to obtain than satellite data. LANDSAT imagery offers practical potential for measuring prairie lake water quality. It provides frequent and total coverage of a region at an inexpensive cost.

REMOTE SENSING OF WATER QUALITY

IN PRAIRIE LAKES

This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Thesis Adviser Date

Head, Biology Department Date

ACKNOWLEDGEMENTS

Sincere appreciation is extended to Dr. Lois Haertel and Dr. Donald Moore for their most helpful guidance and assistance in the planning, development, and writing of this thesis. Without their unselfish assistance, this study would not have been possible.

I also wish to thank Dr. Donald Hales for his review of this manuscript and to Dr. W. Lee Tucker for his help with the statistical methods.

Appreciation is also extended to the Botany-Biology Department, Wildlife and Fisheries Department, Water Resources Institute, and especially to the Remote Sensing Institute for providing the equipment and facilities to conduct this study.

Most of all, I would like to thank my wife, Barbara, for her patience, encouragement, and assistance in the preparation of this manuscript.

Financial support was provided by the Office of Water Resourses Research; project number 13-039-SDAK, allotment number 14-31-0001-5114.

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INTRODUCTION

Evaluating and monitoring lake water quality is an important aspect of water resources management. Most established methods of measuring water quality involve tedious sampling requiring considerable time and expense. They are generally limited to a few specific point sample locations; whereas, remote-sensing techniques can include entire bodies of water and many water bodies over a large area. These remote sensing techniques may provide information which can supplement the established methods to develop sampling procedures which use the advantages of both ground and remote sampling.

When properly employed, the users take advantage of one or more of the following features of remote-sensing data: 1. it provides imagery from a distant vantage point making possible a synoptic view of a large area; 2. it provides a historical record which can be used to detect change in an area with time; and 3. it can expand the limits of the human eye by sensing portions of the spectrum the eye cannot see.

Although many natural waters have been studied by remote sensing techniques, only a few studies have dealt with northern prairie lakes. The majority of work in remote sensing of water quality has included oceans, rivers, and large lakes and reservoirs. The objectives of this study were, first, to quantitatively assess the water quality of the selected lakes and, second, to evaluate the use of remote-sensing data for predicting those water quality parameters.

LITERATURE REVIEW

One advantage of using remote sensing as a monitoring tool for water quality control is the differential penetration of various wavelengths of the energy spectrum into water. This interaction between electromagnetic energy and natural waters has been studied by numerous investigators (Birge and Juday 1932, Clarke and James 1939, Duntley 1963, and Jerlov 1968). In general, ultraviolet energy is reflected directly from the surface, some visible wavelengths penetrate well into the water, and infrared wavelengths are almost entirely absorbed at the near surface. A generalized illustration of depth penetration in pure water of various portions of the electromagnetic spectrum is presented in Fig. 1.

Light is modified not only by the water through which it penetrates but also by absorption and scattering due to particulate and dissolved materials present. This modification of light by materials in the water may serve as a means of identifying different water quality parameters. Scherz et al. (1969) demonstrated that water from lakes in the Madison, Wisconsin area had different reflectance curves. They suggested that the differences could be attributed to the presence of different algal organisms. Reflectance curves of the filtered and unfiltered water from these lake samples are presented in Fig. 2. The relationship between light absorption in water and the reflectivity of chlorophyll is illustrated in Fig. 3. Two peaks occur - at 0.55µm (green region) and especially into the reflective infrared portion of the spectrum.

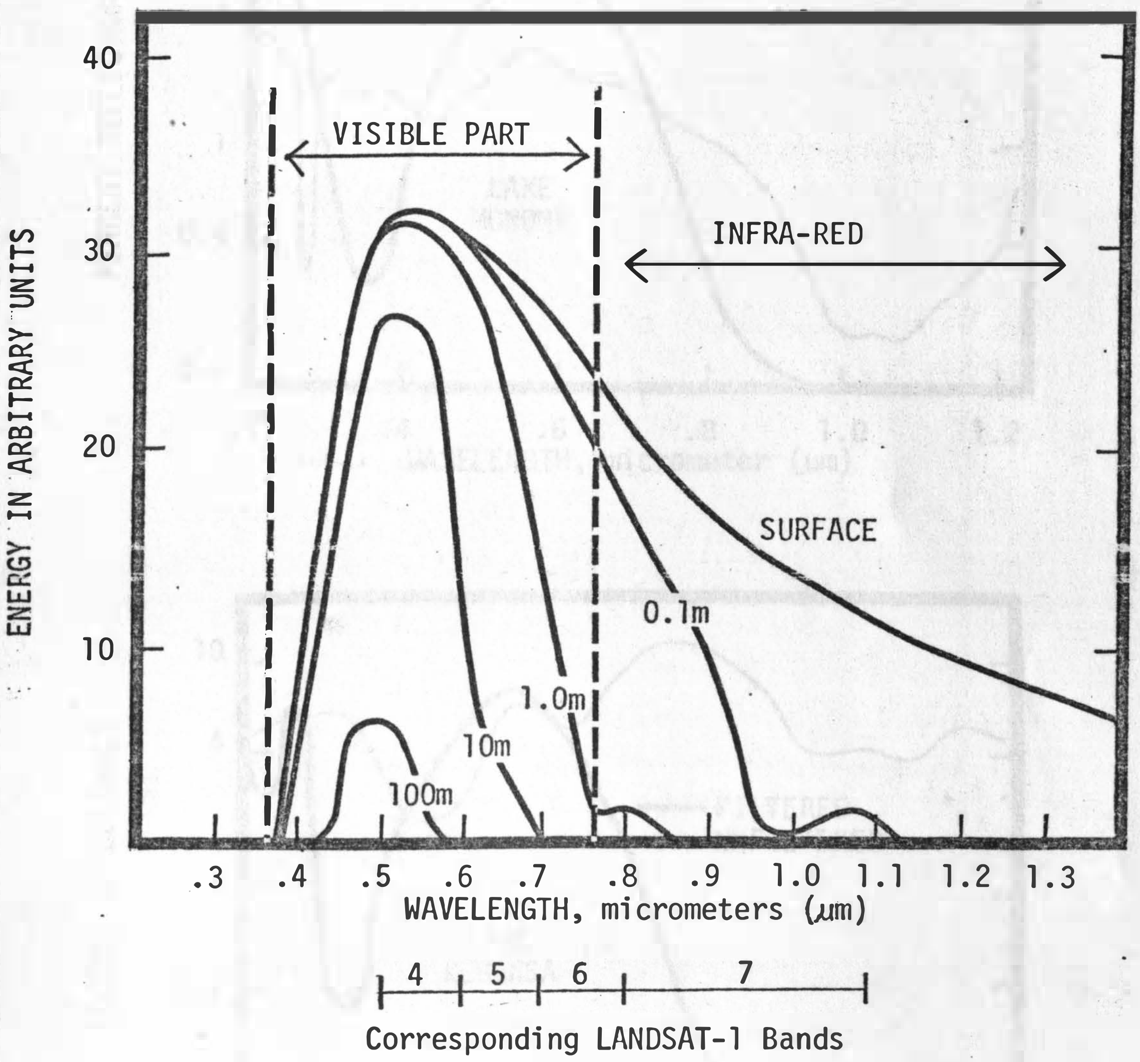


Fig. 1. Energy spectra of sun and sky radiation reaching various depths in pure water. Adapted from Sverdrup et al. (1942).

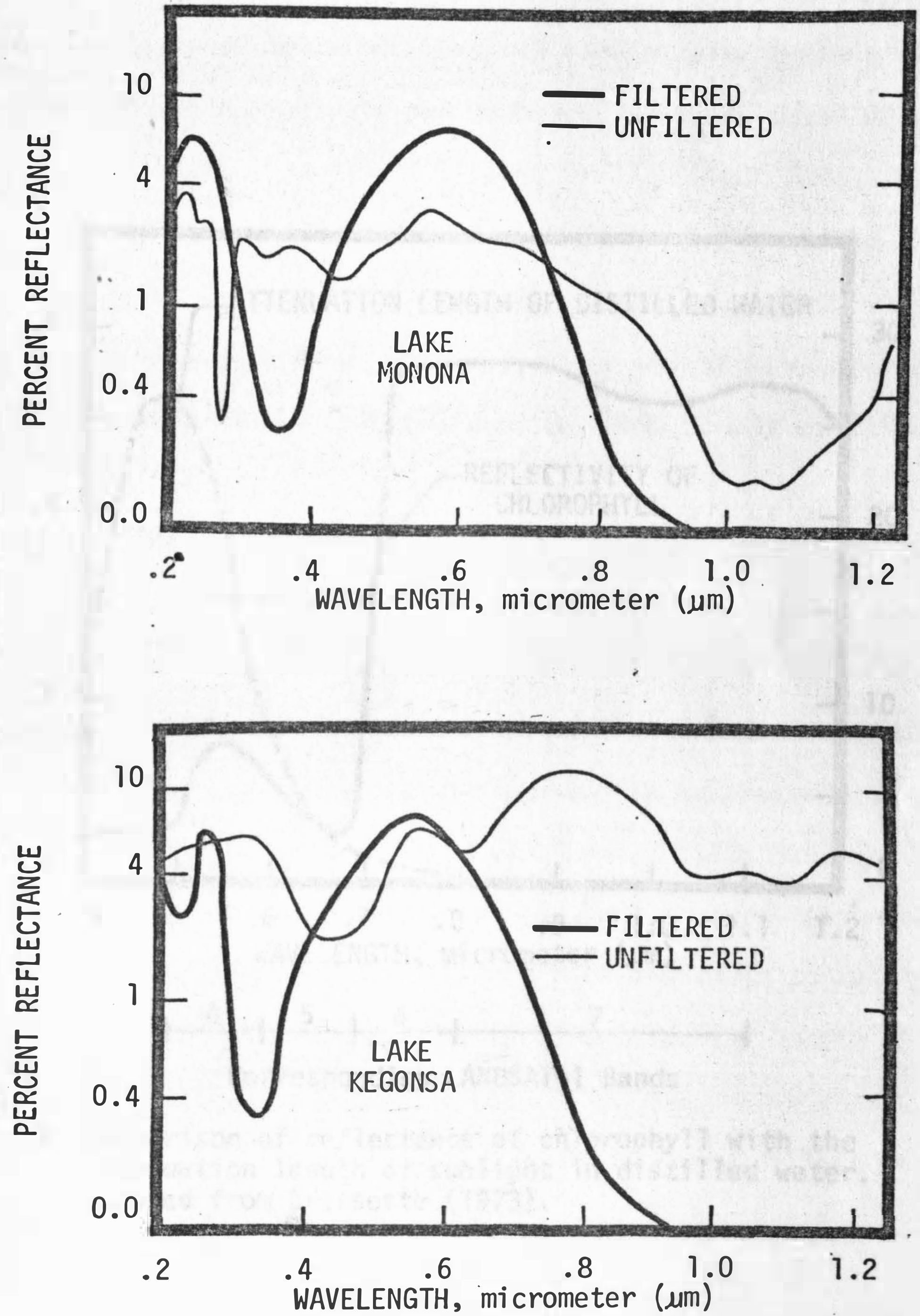


Fig. 2. Reflectance characteristics of filtered and unfiltered water samples from two Madison, Wisconsin lakes. Adapted from Scherz et al. (1969).

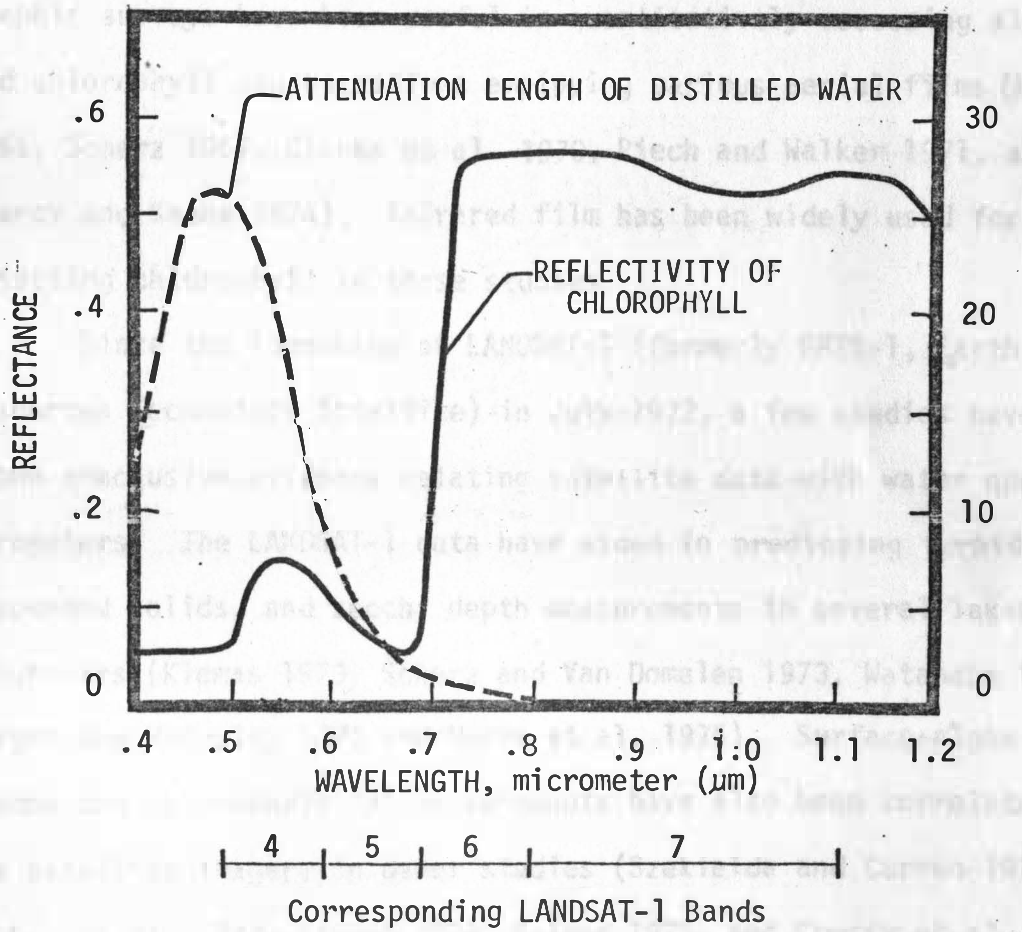


Fig. 3. Comparison of reflectance of chlorophyll with the attenuation length of sunlight in distilled water. Adapted from Bressette (1973).

Low altitude-aircraft was the principal platform used in early remote-sensing investigations. Several studies have correlated aerial film densities with turbidity and suspended solids (Schmer et al. 1972, Klooster and Scherz 1973, and Lillesand 1974). Other aerial photographic surveys have been useful in quantitatively assessing algae and chlorophyll concentrations employing various aerial films (Robinove 1965, Scherz 1967, Clarke et al. 1970, Piech and Walker 1971, and Pearcy and Keene 1974). Infrared film has been widely used for detecting chlorophyll in these studies.

Since the launching of LANDSAT-1 (formerly ERTS-1, Earth Resources Technology Satellite) in July 1972, a few studies have shown conclusive evidence relating satellite data with water quality parameters. The LANDSAT-1 data have aided in predicting turbidity, suspended solids, and secchi depth measurements in several lakes or reservoirs (Klemas 1973, Scherz and Van Domelen 1973, Watanabe 1973, Yarger and McCauley 1975 and Moore et al. 1975). Surface algae blooms and chlorophyll 'a' measurements have also been correlated with the satellite imagery in other studies (Szekielda and Curran 1972, Bowker et al. 1973, Strong 1974, Boland 1975, and Cressy et al. 1975). Methods for lake classification based on reflectance differences have been developed in studies by Moore et al. (1974) and Boland (1975) by correlating water reflectance and various trophic indicators including chlorophyll 'a', turbidity, and secchi depth.

In this study new methods and procedures were developed in addition to evaluating established remote-sensing techniques. The various techniques were combined with satellite, aircraft, and ground imagery to find those methods most capable of predicting the water quality of the selected lakes.

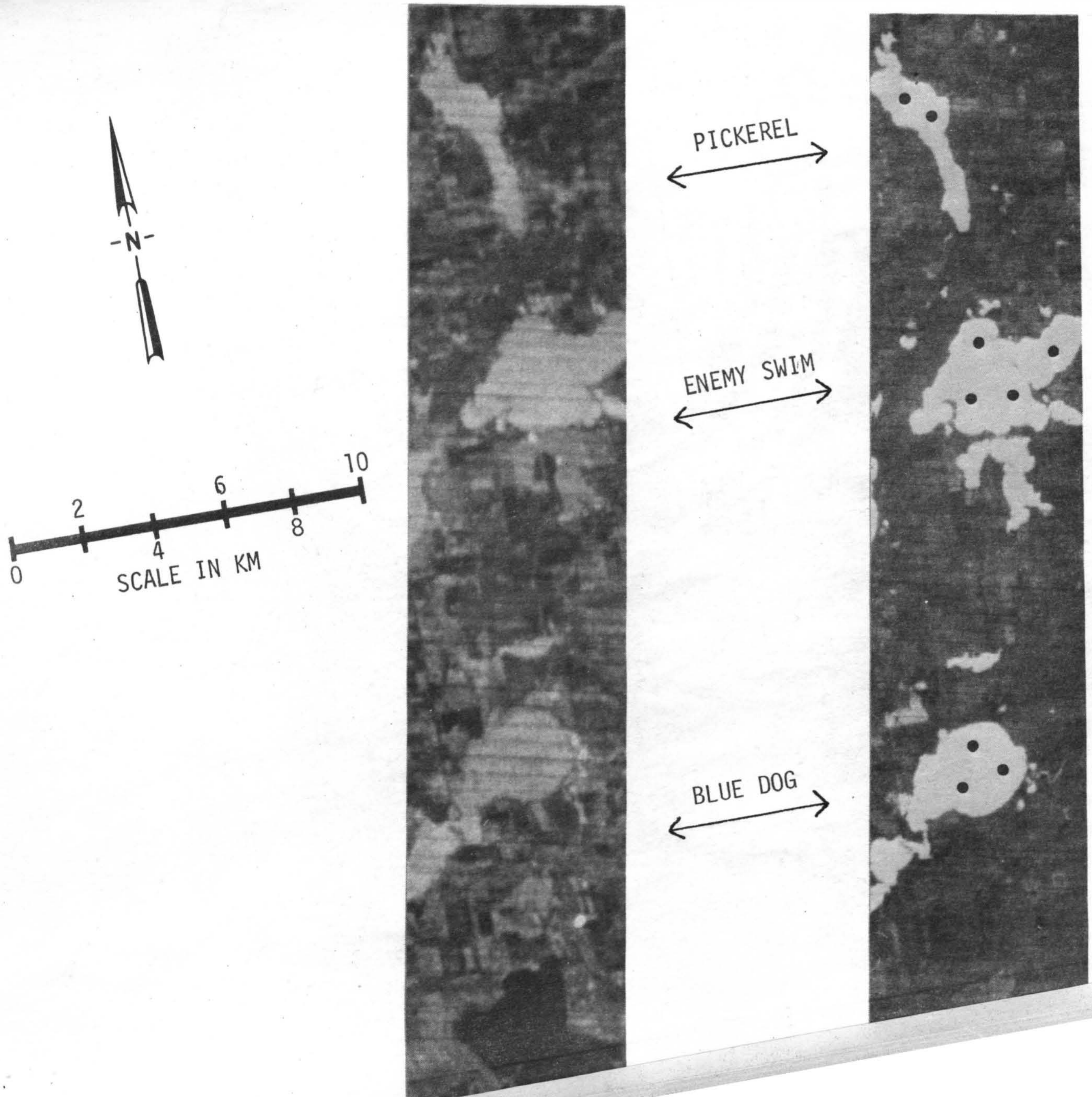
DESCRIPTION OF LAKES

The study involved four lakes, Bitter, Blue Dog, Enemy Swim, and Pickerel in northeastern South Dakota (45° 20' N, 97° 20' W) shown in Fig. 4. The lakes were chosen for their known differences in both water quality and overall reflectance. Among the four lakes, water quality decreases as water depth decreases.

Bitter Lake is the most eutrophic lake and is subject to intense algae blooms and low water transparency. Because of its large size and barren lake shore, winds generate large waves. Wave measurements on a prairie lake of similar size and wind exposure indicated that wave action could directly stir sediments to depths of 15.5Ft 4.7 meters (Haertel 1972). Bitter Lake has a maximum depth of 1.5 4.9Ft meters; therefore, water quality can frequently be influenced by bottom sediments suspended in the water.

Blue Dog is less eutrophic than Bitter Lake; however, it does experience immense bluegreen algae blooms in late summer. Maximum depth is 2.3 7.6Ft meters, again allowing possible sediment suspension by wave action. Approximately one-third of the lake is surrounded by cabins.

Enemy Swim and Pickerel lakes are less eutrophic prairie lakes than either Bitter or Blue Dog. Algae blooms are less frequent. These lakes have maximum depths of 9.7 25.4Ft and 14.5 47.9Ft meters, respectively, so wind generated wave action probably does not stir sediments throughout


N
PICKEREL
ENEMY SWIM
BLUE DOG
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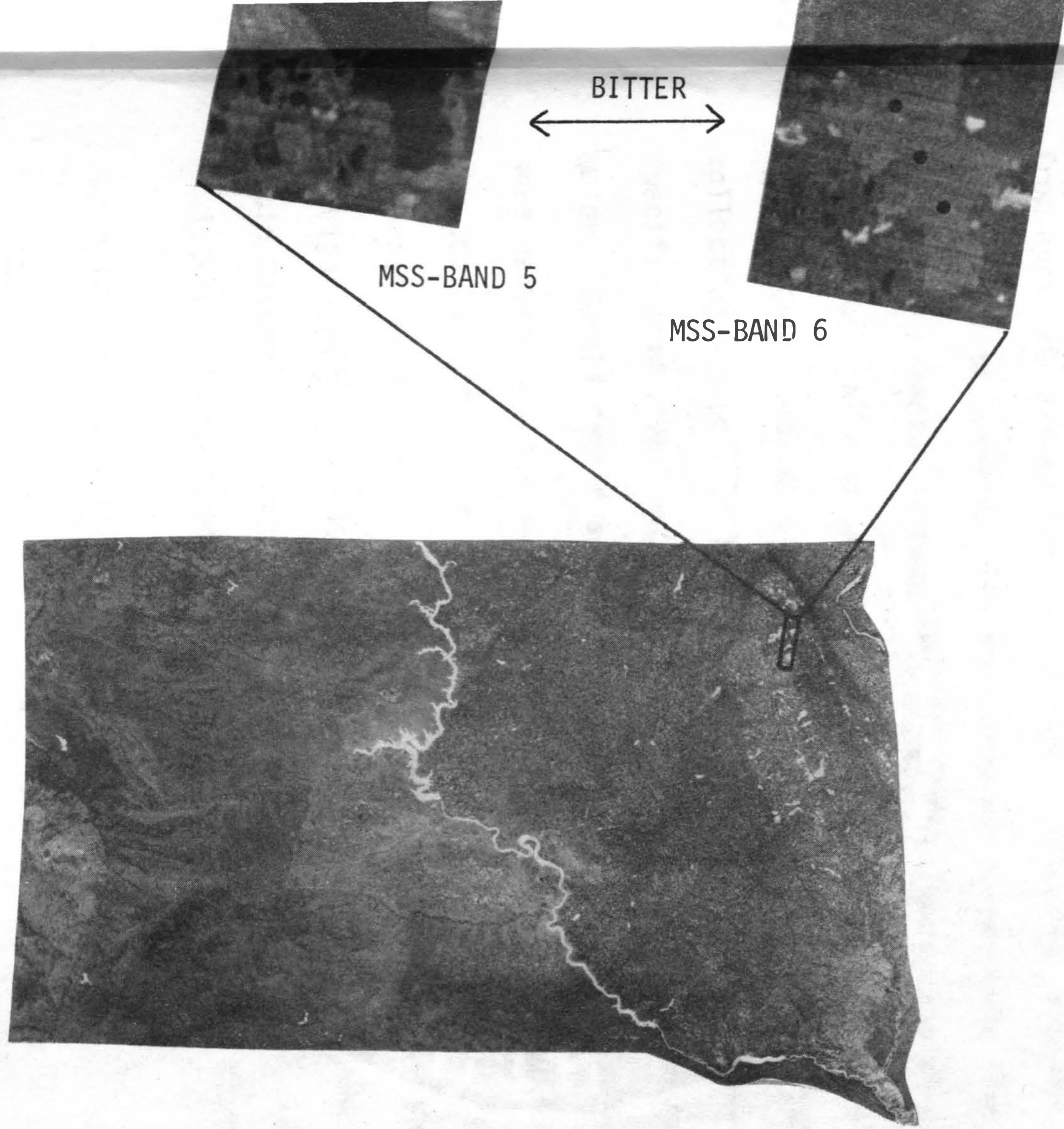

Fig. 4. LANDSAT-1 multispectral negative prints showing location of the study lakes from a South Dakota mosaic and identification of sample sites (•) within the lakes. (ID#1744-16401).

most of the lake area. Recreationally these two lakes are important as cabins, resorts, and parks line the shores.

MATERIALS AND METHODS

Surface (0 to 5 cm) water samples were collected every 18 days from April 20 through October 17, 1974, (excluding September 29 due to high winds) to coincide with the LANDSAT-1 overpasses. Two to four sites were selected in each lake (Fig. 4). Duplicates of all water samples were taken at each site for each of the dates. A time lag of up to six hours between satellite overpass (9:40 a.m. CST) and sample collection was present for some of the samples. Water temperature and specific conductance were measured with a conductivity-temperature meter. Secchi depths were taken with a 20-cm disc and water depths were measured with a sounding line. Chlorophyll 'a' was determined by the acetone extraction method outlined by Strickland and Parsons (1968). Separate water samples collected in dark polyethylene bottles were refrigerated as soon as possible and taken to the Water Quality Lab at South Dakota State University for various water quality measurements. A list of parameters measured and methods used are given in Table 1.

Table 1. Tests and methods used in water quality analyses of water samples taken from the lakes (Am. Public Health Ass. 1971).

Test	Method
Total phosphate	Persulfate digestion
Ortho phosphate	Stannous chloride
Organic nitrogen	Total Kjeldahl
Ammonia	Direct nesslerization
Nitrate	Duicine-sulfanilic
Alkalinity	H_2SO_4 titration

Samples for algae cell counts were collected and preserved in Lugol's solution. Preserved cell-count samples were concentrated in a plankton centrifuge and population densities determined by counting fields from a Sedgeweick-Rafter slide. Fields were randomly counted until 100 individual cells of the most numerous species were recorded (Lund et al. 1958). A colony of Anacystis, Agmenellum, and Gomphosphaeria or a filament of Aphanizomenon was counted as one individual unit. Identification keys used were Smith (1950), Edmondson (1959), Prescott (1962), and Tiffany and Britton (1971).

Daily solar radiation values in langleys/day were obtained from the weather station at South Dakota State University in Brookings, approximately 120-km southeast of the study site. Daily wind velocity was gathered at the National Weather Service in Aberdeen, South Dakota, 95-km west of the lakes. Values for light and wind included measurements for the sampling day alone and an average of seven days previous readings. Daily precipitation recorded for the lakes was from the National Weather Service reporting station at the Waubay National Wildlife Refuge, 2-km west of Enemy Swim. An average daily rainfall of seven previous days was determined.

A four-channel Exotech radiometer (spectral regions corresponding to the four bands on LANDSAT-1) was used to measure radiation incoming to the water surface and reflected from the water surface. For incoming readings the radiometer was held normal to the water surface and for reflectance readings held with the sensors directly over the water approximately 0.5-meter off the lake surface. A diffuser lens on the radiometer approximated a 2π steradian field-of-view for the sensor.

A Macbeth spot densitometer with a 1-mm aperture was used to analyze the remote-sensing imagery. The densitometer directs a light beam of known intensity through the particular lake site on the film transparency, measuring the amount of light transmitted. The value recorded is the optical or film density. The approximate spectral transmittance of each of the four band-pass filters on the densitometer is summarized in Table 2.

Table 2. The approximate spectral transmittance of the Macbeth spot densitometer band-pass filters used in digitizing satellite, aircraft, and ground imagery.

Filter	Spectral transmittance (μm)
blue	0.43 to 0.49
green	0.52 to 0.58
red	0.62 to 0.70
neutral	0.42 to 0.70

Nearly all past work relating to water quality remote-sensing studies using LANDSAT-1 have utilized the data obtained from computer compatible tapes (CCT's). While this first generation product contains the most radiometrically accurate information, the cost of tapes and computer analysis is high. The four transparencies of a LANDSAT-1 MSS scene cost only 10 percent of the listed (August 1975) price for a comparable set of CCT's. Because of the high cost and elaborate equipment required, the approach using CCT's may be totally infeasible on a large scale. This study has used less expensive methods of extracting data from easily accessible 9 x 9 inch (23 x 23 cm) positive transparencies providing a scene having dimensions of 185 x 185 km with a scale of 1:1,000,000.

LANDSAT-1 orbits the earth at an altitude of approximately 915 km viewing the same scene every 18 days. Cloud-free imagery was available only on three dates, June 13 (ID# 1690-16420), July 1 (ID# 1708-16412), and August 6 (ID# 1744-16401). The principal sensor aboard the satellite is the Multispectral Scanner (MSS). The scanner simultaneously measures reflected radiation in four separate wavelength intervals termed bands (Table 3).

Table 3. The approximate wavelength range of the bands aboard the LANDSAT-1 multispectral scanner (MSS).

Designated Band	Wavelength (μm)
MSS 4	0.5 to 0.6
MSS 5	0.6 to 0.7
MSS 6	0.7 to 0.8
MSS 7	0.8 to 1.1

The first step in satellite image interpretation involved recording film densities of the sample sites from each of the four MSS bands. The 1-mm aperture on the spot densitometer when placed over the LANDSAT-1 transparency (1:1,000,000 scale), digitizes a diameter of 1 km. Using only the neutral filter, the aperture of the densitometer was placed over the sample site and a density value was recorded from an average of two readings. These were termed uncorrected density values. Since the relationship between incident radiation and film density of the transparencies is nonlinear and because of possible differences in film processing, corrected values were determined. To do this, a sensitometry strip was placed on each image. The sensitometry strip consisted of a grey scale exposed on the transparency representing 15 known values of incident radiation. The film density of each grey level was measured and plotted against the corresponding grey level. The resulting curve was used to convert the uncorrected film densities of the sample sites to corrected sensitometry values as illustrated in Fig. 5.

Another treatment of satellite data involved determining the approximate radiation viewed by the LANDSAT-1 MSS sensors by converting uncorrected film transmittance values to radiance values. This was done using the following equation (ERTS Data Users Handbook 1972):

$$R = \frac{(Tx - 0.00396)\ Rmax}{0.03929}$$

where Tx equals the transmittance of the LANDSAT-1 transparency
Rmax is the maximum radiation detected by each of the four MSS sensors: Band 4 - 2.48
Band 5 - 2.00
Band 6 - 1.76
Band 7 - 4.60
R equals the radiation received by each MSS band in mw/cm^2

Incoming solar radiation (in the same waveband intervals as the MSS) at the time of LANDSAT-1 overpass was measured directly over the water with the four-channel Exotech radiometer. The incoming radiation was multiplied times the percent radiation reflected (determined with radiometer by ratioing reflected and incoming radiation). This estimated the amount of radiation (mw/cm^2) reflected by each sample site at the time of the LANDSAT-1 overpass. By subtracting the radiation received by the satellite, an estimate of radiation due to atmospheric interference for each date was made.

Atmospheric condition (presence of clouds, fog, smoke, dust, water vapor) affect the quality and quantity of solar radiation passing

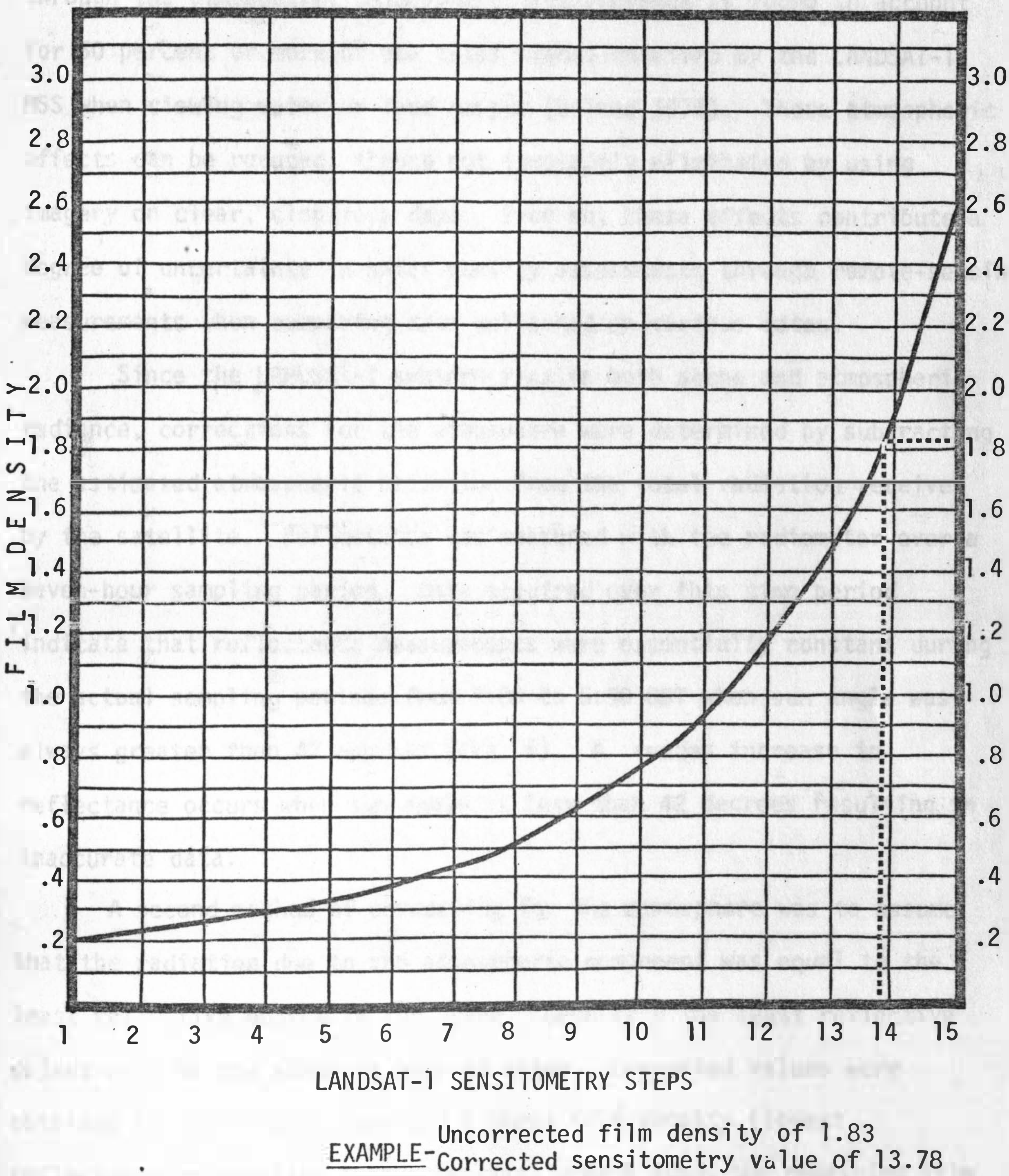

Fig. 5. A typical sensitometry curve produced by plotting film densities of the sensitometry steps used in converting uncorrected film densities to corrected sensitometry values.

through the atmosphere. Atmospheric interference is found to account for 50 percent or more of the total signal received by the LANDSAT-1 MSS when viewing water or land masses (Boland 1975). These atmospheric effects can be reduced; though not completely eliminated by using imagery on clear, cloudless days. Even so, these effects contribute a degree of uncertainty in water quality assessments through remote-sensing measurements when comparing data collected on various dates.

Since the LANDSAT-1 sensors receive both scene and atmospheric radiance, corrections for the atmosphere were determined by subtracting the estimated atmospheric radiation from the total radiation received by the satellite. Reflectance was measured with the radiometer over a seven-hour sampling period. Data acquired over this time period indicate that reflectance measurements were essentially constant during the actual sampling periods from 9:00 to 5:30 CST when sun angle was always greater than 42 degrees (Fig. 6). A sudden increase in reflectance occurs when sun angle is less than 42 degrees resulting in inaccurate data.

A second method of correcting for the atmosphere was to assume that the radiation due to the atmospheric component was equal to the least reflective object in the scene. Generally the least reflective object will be the clearest body of water. Corrected values were obtained by subtracting from the highest film density (lowest reflectance on positive transparencies) in each band, the remaining film densities from the surrounding lake sites. This procedure was investigated and found to improve results in a previous study by Moore et al. (1975).

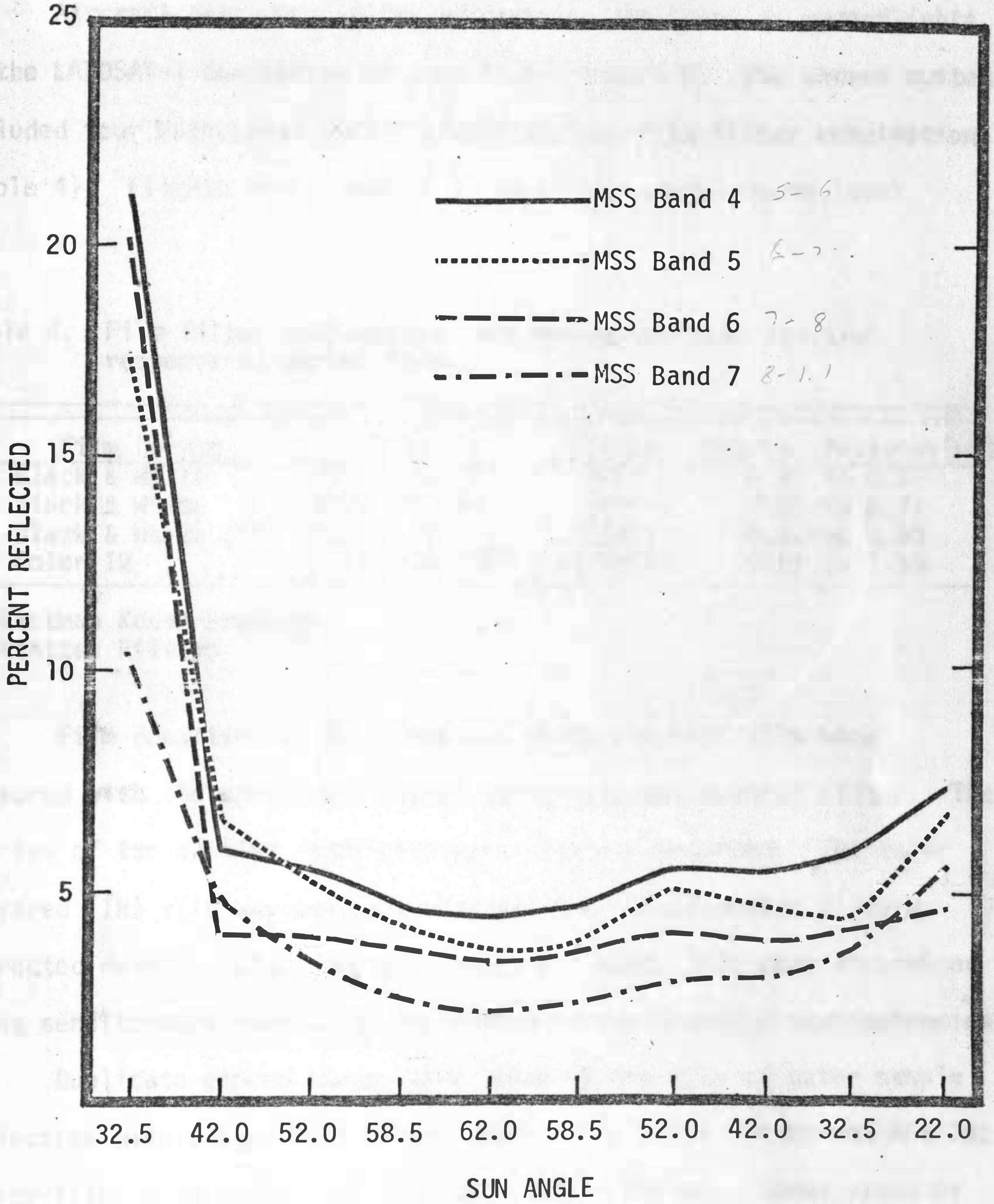

Fig. 6. Comparison of the percent radiation reflected from a lake in the four LANDSAT-1 multispectral scanner (MSS) bands and the sun angle in degrees.

Aircraft data were collected covering the lakes as underflights to the LANDSAT-1 overpasses on June 13 and August 6. The camera system included four Hasselblad 500 EL's with various film-filter combinations (Table 4). Flights were flown at 3,200 meters above ground level.

Table 4. Film-filter combinations and the approximate spectral response of aerial films.

Film Format	Film	Filter	Approx. Response(μm)
Black & White	2402 plus X*	58**	0.47 to 0.61
Black & White	2402 plus X*	25**	0.59 to 0.71
Black & White (IR)	2424 BWIR*	89B**	0.68 to 0.90
Color IR	2443 color IR*	15/30M**	0.51 to 0.90

* Eastman Kodak Products
** Wratten Filters

Film densities of the black and white aircraft film were measured with the spot densitometer using only the neutral filter. The average of two density readings/sample site was recorded. The color infrared (IR) film was analyzed with all four densitometer filters. Corrected density values for only black and white film were determined using sensitometry similar to the method used on LANDSAT-1 transparencies.

Duplicate ground photos were taken at the time of water sample collection with a hand-held 35-mm camera using Kodak Ektachrome ASA 160 (color film) with a Kodak HF-3 (haze) Wratten filter. Three views of the water were photographed; one-half meter directly over the water, at an oblique angle focusing about five-meters away from the boat, and at the horizon including the lake shore. All pictures were taken directly away from the sun to standardize the procedure while minimizing sunglint. The film was digitized into film densities using each of the blue, green, and red filters. Five density readings/filter/sample site were taken. The highest and lowest values were discarded and the three middle values averaged. Film densities from the three filters were ratioed to hopefully reduce the variations caused by sun illumination and sunglint. No corrections for non-linear film response were made.

Statistical analyses including correlation and multiple regression were applied to the data. Regressions involved the water parameters chlorophyll 'a', total algae, and secchi depth as dependent variables and remote-sensing data as the independent variables. Other regressions with water parameters as both dependent and independent variables aided in explaining the relationships between various water quality factors. In several analyses, data from three of the study lakes excluding Bitter were used in addition to regressions including Bitter Lake data alone. This separation was made to determine if Bitter Lake's extremely different water quality and high reflective properties produced consistently different results from the other lakes.

RESULTS AND DISCUSSION

Environmental Data

Seasonal variations of selected water parameters found in the lakes during the April to October sampling period are compared in Table 5. As depth decreased from Pickerel Lake and Enemy Swim Lake to Blue Dog Lake and finally Bitter Lake, algae blooms became more common, nitrate and phosphate concentrations rose, and secchi depths decreased.

Table 5. Low, average, and high values of various water parameters of the study lakes throughout the April to October sampling period.

Lake	Seasonal variation	NO_3 (mg/l N)	Org N (mg/l N)	Ortho P (mg/l P)	Total P (mg/l P)	HCO_3 (mg/l)	CO_3 (mg/l)	Cond (umhos/cm^2)	Secchi (m)	Chlor 'a' (mg/m^3)	Total algae (cells/ml)
	Low	0.097	6.87	0.046	0.287	464	158	10,100	0.10	60.2	174,000
Bitter	Average	0.174	8.81	0.139	0.499	518	353	11,904	0.10	136.2	664,600
	High	0.330	16.17	0.424	0.743	796	555	18,900	0.20	241.0	1,770,800
	Low	0.012	0.50	0.000	0.033	208	0.6	302	0.15	4.0	1,600
Blue	Average	0.064	1.34	0.013	0.067	236	12.0	378	0.46	40.6	5,100
Dog	High	0.180	4.79	0.027	0.104	261	22.0	436	1.00	262.6	11,400
	Low	0.006	0.68	0.000	0.016	232	10.7	299	0.85	3.3	1,800
Enemy	Average	0.018	0.71	0.004	0.037	244	20.4	380	1.70	10.2	4,900
Swim	High	0.035	0.95	0.007	0.065	257	26.7	560	2.90	21.9	8,300
	Low	0.000	0.50	0.000	0.020	212	0.0	322	1.10	3.2	500
Pickerel	Average	0.023	0.71	0.003	0.039	236	13.3	386	2.22	12.3	5,600
	High	0.050	0.95	0.008	0.082	254	22.5	445	5.40	20.7	10,500

Algae have generally been assumed to require nitrogen (NO_3-N) and phosphorus (ortho PO_4-P) in a ratio of 7.2:1 by weight (Vollenwieder 1968 and Bachman and Jones 1974). The average NO_3-N to PO_4-P ratios of the lakes during the sampling season were as follows: Bitter Lake 1.3:1, Blue Dog 5.3:1, Enemy Swim 5.0:1, and Pickerel 9.2:1. These values suggest a greater possibility for nitrogen limitation than phosphorus limitation in all lakes but Pickerel.

The results of simple linear correlation analysis of water quality parameters are presented in Table 6. Chlorophyll 'a' was significantly correlated with all variables listed. Since increases in nutrient levels above limiting values usually cause an increase in algae growth raising the chlorophyll concentration, the positive correlations with NO_3-N (0.625**) and ortho PO_4-P (0.486**) were expected. Part of the organic nitrogen and total phosphate is composed of living algae so these part-whole correlations have no meaning.

Water depth (-0.451**) and secchi depth (-0.440**) were negatively correlated with chlorophyll 'a'. Decreased water depth made possible more influence of wind and wave action on stirring of bottom sediments and release of nutrients into the water column. These nutrients subsequently may stimulate increased chlorophyll production. Increased chlorophyll and suspended sediments are both sources of turbidity and may help contribute to decreased secchi depths. An inverse relationship between sunlight and chlorophyll (-0.195**) may have simply resulted from a normal seasonal difference. Higher chlorophyll concentrations existed in all lakes during April and October

Table 6. Correlation matrix (r) of environmental data from all four study lakes on all sampling dates .

	Chlor 'a'	Ortho P	Total P	NO_3	Org N	Secchi	Depth	Light	Wind	Cells
Chlor 'a'(mg/m^3)	1.000	0.486**	0.592**	0.625**	0.755**	-0.440**	-0.451**	-0.195**	0.172**	0.565**
Ortho P(mg/l P)		1.000	0.874**	0.629**	0.750**	-0.451**	-0.498**	0.132*	0.048	0.592**
Total P(mg/l P)			1.000	0.811**	0.931**	-0.529**	-0.580**	0.034	0.019	0.828**
NO_3(mg/l N)				1.000	0.869**	-0.541**	-0.607**	-0.141**	0.034	0.837**
Org N(mg/l N)					1.000	-0.524**	-0.576**	-0.097	0.022	0.897**
Secchi depth(m)						1.000	0.768**	0.021	-0.040	-0.427**
Water depth(m)							1.000	-0.015	-0.027	-0.475**
Light-7 day ave.(langleys/day)								1.000	-0.097	-0.113
Wind-7 day ave.(km/h)									1.000	0.058
Total algae(cells/ml)										1.000

* denotes significance at the .05 level
** denotes significance at the .01 level

when incoming solar radiation was relatively low. A high correlation may be expected between chlorophyll 'a' and total algae (0.565**), however, Table 5 provides a possible explanation. In Blue Dog high chlorophyll'a' levels accompanied relatively low algae cell counts. This may be a result of several factors: algae colonies being counted as single cells, the difference in algae cell sizes, the physiological state and overall health of the cell, and the fact that chlorophyll 'a' is only one of several pigments found in algae. Rainfall and water temperature were not significantly correlated with any water parameters using simple linear regression and were not included in Table 6.

Results of multiple regression analysis of various environmental data appear in Table 7. Nitrate level was the most important factor significantly correlated with chlorophyll 'a' and total cell counts in four of six analyses. These analyses along with the NO_3 - PO_4 ratios of the lakes would support findings of past studies (Haertel 1972) indicating that nitrate is the major factor correlated with increased abundance of algae in these prairie lakes. Sunlight and ortho phosphate were also positively correlated with chlorophyll in Table 6, but the fraction of variation ascribed to these factors by multiple regression was much lower than that ascribed to nitrate. In all three regressions the relationship between chlorophyll and total cells and water temperature was negative. Levels of chlorophyll and total algae early and late in the sampling period were high when water temperatures were lowest.

Water depth, rainfall, total algae, and sunlight were the major significant variables correlated with concentration of nitrates and

Table 7. Multiple regression results of environmental data from all four study lakes, from Bitter Lake excluded, and from Bitter Lake alone.

Regression variable		all lakes	Bitter excluded		Bitter only	
Dependent	Independent	r^2	Independent	r^2	Independent	r^2
Chlorophyll 'a'	nitrate	0.390**	nitrate	0.216**	water temp	0.661**
	water temp	0.030**(-)	light-7 day ave	0.034**(-)	ortho P	0.008
	ortho P	0.019**	ortho P	0.008	light-7 day ave	0.008(-)
	light-7 day ave	0.007(-)	wind-7 day ave	0.001	nitrate	0.002
	wind-7 day ave	0.000	water temp	0.001(-)	wind-7 day ave	0.001
Total algae	nitrate	0.698**	light-7 day ave	0.095**(-)	nitrate	0.733**
	ortho P	0.007*	wind-7 day ave	0.013	water temp	0.062**(-)
	wind-7 day ave	0.001	nitrate	0.001	light-7 day ave	0.032**(-)
	light-7 day ave	0.000	ortho P	0.002(-)	wind-7 day ave	0.031**
	water temp	0.001(-)	water temp	0.000	ortho P	0.029**(-)
Nitrate	total algae	0.608**	water depth	0.197**(-)	water depth	0.771**(-)
	water depth	0.057*(-)	light-7 day ave	0.036**(-)	total algae	0.048**
	rainfall	0.005**(-)	water temp	0.009(-)	wind-7 day ave	0.041**(-)
	light-7 day ave	0.003(-)	wind-7 day ave	0.001	rainfall	0.032**(-)
	wind-7 day ave	0.003	rainfall	0.002(-)	light-7 day ave	0.023**(-)
	water temp	0.003(-)	total algae	0.000	water temp	0.026**(-)
Ortho P	total algae	0.351**	water depth	0.261**(-)	rainfall	0.278**(-)
	water depth	0.061**(-)	rainfall	0.007**(-)	water temp	0.112**
	light-7 day ave	0.033**	wind-7 day ave	0.006**(-)	wind-7 day ave	0.174**
	rainfall	0.025**(-)	light-7 day ave	0.005**	water depth	0.047**(-)
	water temp	0.003	water temp	0.019**(-)	total algae	0.106**(-)
	wind-7 day ave	0.000	total algae	0.002	light-7 day ave	0.007
Secchi depth	water depth	0.590**	water depth	0.446**	no variation dependent variable	
	wind/samp. day	0.113**(-)	wind/samp. day	0.205**(-)		
	bicarbonate	0.004(-)	chlorophyll	0.009*(-)		
	chlorophyll	0.001(-)	carbonate	0.002(-)		
	carbonate	0.000	bicarbonate	0.001(-)		

* denotes significance at the .05 level
** denotes significance at the .01 level
(-) indicates an inverse relationship between the two variables in the simple linear regression

phosphates in all four lakes. Wave action extending to the lake bottom in shallow areas disturbing nitrates and phosphates from the sediments may have been the reason for the negative correlation with depth. An exceptionally dry summer caused lake water levels to drop 0.5 to 1.0 meter. This could explain the negative correlation with rainfall. Heavy rains from April to June might have diluted rather than enriched the water with nitrates and phosphates and little rain the remainder of the summer may have concentrated the nutrients. Generally total algae increased as the summer progressed (June through October) as did sunlight in langleys/day.

Over 65 percent of the variation in secchi depth could be accounted for by variation in water depth and wind velocity on the sampling day. The greater disturbance of bottom sediments in shallow lakes on windy days could result immediately in increased turbidity and eventually in increased chlorophyll, total algae, etc. all contributing to decreased secchi depth readings.

Remote-Sensing Data

Reflective properties, like water quality, were consistently different in the four lakes. These different reflective patterns in each of the four bands are illustrated in Table 8 using three remote sensing methods. As the percent reflectance increases, the optical density on positive transparencies decreases. The overall quality of lake water decreases in the lakes from top to bottom with Enemy Swim and Pickerel being very similar. The increased reflectance that

Table 8. Different reflective patterns of the study lakes (in the four MSS bands) using three remote-sensing methods.

	MSS Band	% reflected-ground radiometer	LANDSAT-1 uncorrected film density	LANDSAT-1 corrected sensitometry
Bitter	4	10.3	0.68	10.62
	5	10.2	0.86	11.58
	6	8.1	1.04	12.58
	7	5.8	1.47	13.76
Blue Dog	4	4.8	0.83	11.67
	5	5.2	0.97	12.15
	6	3.1	1.24	13.13
	7	2.3	1.66	14.07
Enemy Swim	4	4.6	0.99	12.42
	5	3.8	1.24	13.14
	6	2.7	1.57	13.88
	7	2.4	1.85	14.37
Pickerel	4	4.0	1.00	12.45
	5	3.6	1.30	13.26
	6	2.7	1.56	13.84
	7	2.4	1.85	14.37

accompanies poorer water quality is primarily due to increased suspended and dissolved material.

Multiple regression results indicate that of the LANDSAT-1 MSS spectral regions, Band 4 had the highest correlation with chlorophyll (Table 9). In three of the satellite estimates (B, E, and H) chlorophyll concentration, Band 4 alone accounted for at least 71 percent of the variation. Because of the relatively deep penetration of green light in water, Band 4 could reflect from chlorophyll found beneath the water surface as well as that on the water surface (Fig. 3). The two ground-based radiometer estimates of reflectance (G and I) require a ratioing of incoming and reflected values. Past studies (Yarger and McCauley 1975 and Boland 1975) have shown that this ratioing considerably reduces the interference due to atmospheric scattering of light. If this is true, then data from these two methods (G and I) should be free of most atmospheric attenuation. With these methods, Band 7 was best for predicting chlorophyll. Reflectivity curves on Fig. 3 indicate that infrared light (Band 7) has little reflectance from water unless chlorophyll is found on or near the water surface. Regressions with aerial film data (J and K) reveal that the two types of infrared film, color and black and white, account for 82 percent of the variation in chlorophyll consistent with reflectance curves from Fig. 3. The ground photo taken directly over the water ratioing the red and green filters provided the largest r^2 value.

Table 9. Multiple regression results of chlorophyll and twelve estimates of ground, aircraft, and LANDSAT-1 MSS data. (Final regression equations for A.-L. are given in Appendix, Table 18.)

	r^2		r^2		r^2
A. Band 6	0.629**	E. Band 4	0.754**	I. Band 7	0.398**
Band 7	0.042	Band 7	0.172**	Band 5	0.039**
Band 5	0.003*	Band 6	0.004	Band 6	0.057**
Band 4	0.020*	Band 5	0.001	Band 4	0.006
B. Band 4	0.770**	F. Band 6	0.716**	J. IR-R	0.820**
Band 7	0.026**	Band 4	0.019**	BW-G	0.020**
Band 5	0.010	Band 5	0.079**	IR-B	0.075**
Band 6	0.000	Band 7	0.000	IR-G	0.017**
				BW-IR	0.002
C. Band 5	0.126**	G. Band 7	0.284**	K. BW-IR	0.822**
Band 7	0.248**	Band 4	0.074**	BW-G	0.046**
Band 4	0.092**	Band 6	0.014**	BW-R	0.000
Band 6	0.015	Band 5	0.038**		
D. Band 4	0.359**	H. Band 4	0.715**	L. Over R/G	0.113**
Band 7	0.237**	Band 7	0.037**	Obl R/G	0.024*
Band 6	0.212**	Band 6	0.000	Over R/B	0.013
Band 5	0.051	Band 5	0.000	Obl B/G	0.007
				Hor R/G	0.005

* denotes significance at .05 level
** denotes significance at .01 level

A. LANDSAT-1 uncorrected film density (72 obs.)
B. LANDSAT-1 corrected sensitometry (72 obs.)
C. LANDSAT-1 corrected sensitometry excluding Bitter (54 obs.)
D. LANDSAT-1 corrected sensitometry-Bitter only (18 obs.)
E. LANDSAT-1 corrected for atmosphere-reflected minus received (48 obs.)
F. LANDSAT-1 corrected for atmosphere-least reflective method (72 obs.)
G. Radiation reflected from water-% reflected times incoming (162 obs.)
H. Radiation received by LANDSAT-1 (56 obs.)
I. Percent radiation reflected from water-ground radiometer (160 obs.)
J. Aircraft uncorrected film density (IR-B:color IR/blue filter)(24 obs.)
K. Aircraft corrected sensitometry(34 obs.)
L. Ground photo density ratios (Hor R/G:horizon red/blue ratio)(196 obs.)

r^2 values indicate the % variation in chlorophyll which can be explained by variation in remote-sensing data

No one MSS band can clearly be singled out in predicting total algae from the nine estimates of satellite data (Table 10). Band 5 does, however, have more significant results than the other bands. In correcting for atmosphere using the least reflective method, Band 5 accounted for 85.2 percent of the variation in total algae. Only ground-based reflectance measurements (G and I) resulted in Band 6 significantly predicting total algae. In aerial and ground photos, results similar to chlorophyll occurred with total algae. Corrected black and white infrared aerial film and ground photos over the water ratioing red and green filter readings produced the best prediction of total algae.

The regression results of secchi depth and remote-sensing data are summarized in Table 11. Findings show that significant results consistantly obtained with MSS Band 5. Band 4 has the deepest penetration in distilled water but as dissolved substances increase, water becomes more transmissive in the orange and red (Band 5) wavelengths than in shorter wavelengths (Boland 1975). Penetrating the deepest, Band 5 would be more capable of detecting variation in secchi depth in turbid waters. Correcting the aerial film with sensitometry did not improve results. Again for the ground photos, ratioing the red and green filters gave the best prediction of the water quality variable.

Significant correlations existed between several water parameters such as water depth, NO_3, and PO_4 and various remote-sensing data but were not reported. Bands 4 and 5 probably cannot penetrate deeper than secchi depth readings (Boland 1975). Since no secchi readings reached

Table 10. Multiple regression results of total algae and twelve estimates of ground, aircraft, and LANDSAT-1 MSS data. (Final regression equations for A.-L. are given in Appendix, Table 19.)

		r^2			r^2			r^2
A.	Band 6	0.378**	E.	Band 4	0.815**	I.	Band 6	0.403**
	Band 7	0.194**		Band 6	0.030**		Band 4	0.002
	Band 5	0.001		Band 5	0.072**		Band 5	0.006
	Band 4	0.000		Band 7	0.018**		Band 7	0.000
B.	Band 4	0.818**	F.	Band 5	0.852**	J.	IR-B	0.481**
	Band 6	0.003**		Band 6	0.016**		IR-G	0.338**
	Band 7	0.038**		Band 7	0.007		BW-G	0.097**
	Band 5	0.004		Band 4	0.001		IR-R	0.015**
							IR-V	0.013*
C.	Band 5	0.181**	G.	Band 6	0.374**	K.	BW-IR	0.820**
	Band 4	0.043		Band 4	0.003		BW-G	0.007
	Band 6	0.011		Band 7	0.001		BW-R	0.001
	Band 7	0.002		Band 5	0.001			
D.	Band 5	0.700**	H.	Band 5	0.427**	L.	Over R/G	0.155**
	Band 6	0.089*		Band 7	0.305**		Over B/G	0.017**
	Band 7	0.042		Band 6	0.063**		Hor R/G	0.017**
	Band 4	0.024		Band 4	0.002		Hor R/B	0.041**
							Obl B/G	0.011

* denotes significance at .05 level
** denotes significance at .01 level

A. LANDSAT-1 uncorrected film density (72 obs.)
B. LANDSAT-1 corrected sensitometry (72 obs.)
C. LANDSAT-1 corrected sensitometry excluding Bitter (54 obs.)
D. LANDSAT-1 corrected sensitometry- Bitter only (18 obs.)
E. LANDSAT-1 corrected for atmosphere-reflected minus received (48 obs.)
F. LANDSAT-1 corrected for atmosphere-least reflective method (72 obs.)
G. Radiation reflected from water-% reflected times incoming (162 obs.)
H. Radiation received by LANDSAT-1 (56 obs.)
I. Percent radiation reflected from water-ground radiometer (160 obs.)
J. Aircraft uncorrected film density (IR-B: color IR/blue filter) (24 obs.)
K. Aircraft corrected sensitometry (34 obs.)
L. Ground photo density ratios (Hor R/G: horizon red/blue ratio) (196 obs.)

r^2 values indicate the % variation in total algae which can be explained by variation in remote-sensing data

Table 11. Multiple regression results of secchi depth and twelve estimates of ground, aircraft, and LANDSAT-1 MSS data. (Final regression equations for A.-L. are given in Appendix, Table 20.)

	r^2		r^2		r^2
A. Band 5	0.617**	E. Band 4	0.149**	I. Band 5	0.271**
Band 7	0.179**	Band 6	0.326**	Band 4	0.018**
Band 6	0.016*	Band 5	0.024	Band 7	0.007**
Band 4	0.014*	Band 7	0.009	Band 6	0.041**
B. Band 5	0.506**	F. Band 5	0.341**	J. IR-B	0.658**
Band 6	0.247**	Band 6	0.020	BW-G	0.074**
Band 7	0.045*	Band 7	0.016	IR-R	0.006**
Band 4	0.000	Band 4	0.002	BW-IR	0.031**
				IR-G	0.035**
C. Band 5	0.628**	G. Band 5	0.264**	K. BW-G	0.620**
Band 6	0.216**	Band 6	0.005*	BW-IR	0.015*
Band 4	0.002	Band 7	0.018*	BW-R	0.054*
Band 7	0.000	Band 4	0.002		
D. no variation in secchi depth		H. Band 5	0.400**	L. Over R/G	0.515**
		Band 7	0.106**	Over R/B	0.040**
		Band 4	0.009*	Hor R/G	0.010**
		Band 6	0.041*	Obl B/G	0.021**
				Obl R/B	0.011*

* denotes significance at .05 level
** denotes significance at .01 level

A. LANDSAT-1 uncorrected film density (72 obs.)
B. LANDSAT-1 corrected sensitometry (72 obs.)
C. LANDSAT-1 corrected sensitometry excluding Bitter (54 obs.)
D. LANDSAT-1 corrected sensitometry-Bitter only (18 obs.)
E. LANDSAT-1 corrected for atmosphere-reflected minus received (48 obs.)
F. LANDSAT-1 corrected for atmosphere-least reflective method (72 obs.)
G. Radiation reflected from water-% reflected times incoming (162 obs.)
H. Radiation received by LANDSAT-1 (56 obs.)
I. Percent radiation reflected from water-ground radiometer (160 obs.)
J. Aircraft uncorrected film density (IR-B:color IR/blue filter) (24 obs.)
K. Aircraft corrected sensitometry(34 obs.)
L. Ground photo density ratios (Hor R/G:horizon red/blue ratio)(196 obs.)

r^2 values indicate the % variation in secchi depth which can be explained by variation in remote-sensing data the bottom of any sample site, it was assumed that a factor other than water depth was responsible for the variation in remote sensing measurements. Despite the significant regression with nitrate and phosphate, photography and multispectral scanners probably cannot directly determine nutrients in the water (Scherz 1971). Reflectance is primarily altered by solids in the water, hence significant results with various nutrients may actually be due to changes in chlorophyll, total algae, secchi depth, or suspended sediments.

Correlations between ground radiometer readings and two estimates of LANDSAT-1 data are shown in Table 12.

Table 12. Correlation coefficients (r) comparing radiation reflected from the water using the ground radiometer with two estimates of LANDSAT-1 MSS data.

		Percent Reflected-Ground Radiometer			
		r	r		
LANDSAT-1 corrected sensitometry	Band 4	-0.921**	0.867**	Band 4	LANDSAT-1 corrected for sensitometry and atmosphere
	Band 5	-0.914**	0.881**	Band 5	
	Band 6	-0.848**	0.882**	Band 6	
	Band 7	-0.625**	0.770**	Band 7	

** denotes significance at the .01 level

The assumption was made that ground-based radiometer readings (percent reflectance) were void of most variations caused by skylight irradiance and contained the most accurate data available. Correlations were run to see whether correcting for sensitometry alone or correcting for both sensitometry and atmospheric interference (least reflective method) provided the more accurate results. For the three dates of imagery analyzed, correcting for sensitometry alone improved results with Band 4 and 5 making the correction for atmosphere unnecessary. Results with

Bands 6 and 7 were improved if the correction for atmosphere was also applied. The best correction would depend on which LANDSAT-1 bands were being considered.

Various investigators (Yarger and McCauley 1975 and Boland 1975) have ratioed different LANDSAT-1 bands to help reduce atmospheric interference and minimize changes due to sun angle. Ratioed and non ratioed LANDSAT-1 MSS data were correlated with three water parameters (Table 13) to see if ratioing actually did improve results. The findings clearly show that ratioing different bands did not improve the correlations. Better results were obtained instead with non-ratioed data corrected for sensitometry and corrected for both sensitometry and atmosphere.

Table 13. Correlation coefficients (r) of non-ratioed and ratioed estimates of two sets of LANDSAT-1 MSS data and three water quality parameters.

	LANDSAT-1 corrected sensitometry				LANDSAT-1 corrected for atmosphere			
	Band	r	Ratio	r	Band	r	Ratio	r
Chlorophyll *a* (mg/m^3)	4	-0.878**	7/4	0.810**	6	0.846**	6/5	0.506**
	6	-0.871**	7/5	0.743**	4	0.836**	7/4	0.485**
	5	-0.841**	6/5	0.389**	7	0.831**	7/5	0.345**
	7	-0.825**	6/4	0.370**	5	0.778**	5/4	0.131**
Total algae (cells/ml)	4	0.904**	7/5	0.884**	5	0.923**	7/4	0.449**
	6	0.877**	7/4	0.730**	6	0.918**	6/5	0.369**
	5	0.871**	6/5	0.512**	4	0.889**	7/5	0.257**
	7	0.733**	6/4	0.460**	7	0.842**	5/4	0.127*
Secchi depth (m)	5	0.711**	6/5	-0.798**	5	-0.584**	5/4	-0.479**
	4	0.620**	7/4	-0.707**	4	-0.550**	6/5	-0.438**
	6	0.562**	7/5	-0.702**	6	-0.513**	7/5	-0.158
	7	0.514**	5/4	0.396**	7	-0.471**	7/4	-0.155

* denotes significance at .05 level
** denotes significance at .01 level

CONCLUSIONS

The methods of data acquisition used in the study were oriented to the user with access to inexpensive equipment. Procurement of the remote-sensing imagery (especially ground and satellite) and subsequent data reduction with the spot densitometer offer inexpensive yet relatively accurate water quality predictions. This data reduction demonstrated that a high fraction of variability in chlorophyll, total algae, and water transparency as measured by secchi depth can be significantly predicted by LANDSAT-1 imagery and aerial and ground photography. The MSS Band 4 aboard LANDSAT-1 best predicted chlorophyll concentration in the study lakes. From multiple regression results, total algae, and secchi depths were predicted best with MSS Band 5. Low flying aircraft photography detected chlorophyll and total algae with black and white IR film and secchi depth with black and white film exposed with a green band-pass filter. The ground photographs taken directly over the water ratioing film densities from the red and green densitometer filters correlated best with all three water parameters. Generally correcting for sensitometry and/or atmospheric interference improved results whereas ratioing various wavelengths or bands did not. The tonal patterns present on the remote-sensing imagery were significantly related to the water parameters studied; however, since the water parameters were all significantly correlated with each other, the remote sensing techniques could not be used to separate any specific parameters. This may not be a serious problem in prairie lake management since decreased water depth and secchi depth usually occur together with increased nutrients, chlorophyll, and total algae.

Extensive ground-based radiometer readings and ground photography at this time seem impractical for predicting water quality despite their significant results. The time involved on the ground with these methods would justify collection of actual water samples.

Aircraft data, although more expensive and less synoptic than satellite data, can be useful in identifying point sources of contaminants because of its lower altitude and higher resolution.

Satellite imagery appears to be the most desirable data for the remote sensing of water quality in operational programs. Repetitive coverage and easily obtainable imagery encompassing many lakes/scene at an inexpensive price are characteristics of LANDSAT-1 important in prairie lake management. LANDSAT-1 can be used to locate areas of algae blooms, high suspended sediment concentrations, aquatic vegetation, etc., and can also determine where representative water samples should be collected within a lake. Lakes can also be classified as to trophic levels on the basis of reflective patterns. The historic data provides an excellent basis for determining tonal changes with time since LANDSAT-1 imagery is available throughout the season where cloud cover permits since July 1972.

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APPENDIX

Table 14. Correlation coefficients (r) of environmental data from all four study lakes, from Bitter Lake excluded, and from Bitter Lake alone.

Regression variables		all lakes	Bitter excluded		Bitter only	
Dependent	Independent	r	Independent	r	Independent	r
	nitrate	0.625**	nitrate	0.464**	water temp	-0.813**
	water temp	0.224**	light-7 day ave	-0.275**	ortho P	0.072
Chlorophyll 'a'	ortho P	0.486**	ortho P	0.172**	light-7 day ave	-0.333*
	light-7 day ave	0.195**	wind-7 day ave	0.048	nitrate	0.200
	wind-7 day ave	0.172*	water temp	-0.138	wind-7 day ave	0.693**
	nitrate	0.836**	light-7 day ave	-0.309**	nitrate	0.856**
	ortho P	0.592**	wind-7 day ave	0.152*	water temp	-0.364**
Total algae	wind-7 day ave	0.058	nitrate	0.102	light-7 day ave	-0.640**
	light-7 day ave	-0.112	ortho P	-0.027	wind-7 day ave	0.203
	water temp	-0.078	water temp	-0.229**	ortho P	-0.109
	total algae	0.836**	water depth	-0.444**	water depth	-0.878**
	water depth	-0.607**	light-7 day ave	-0.203**	total algae	0.856**
Nitrate	rainfall	-0.088	water temp	-0.160*	wind-7 day ave	-0.044
	light-7 day ave	-0.141*	wind-7 day ave	0.109	rainfall	-0.267*
	wind-7 day ave	0.034	rainfall	-0.110	light-7 day ave	-0.494**
	water temp	-0.083	total alge	0.102	water temp	-0.136
	total algae	0.592**	water depth	-0.511	rainfall	-0.527**
	water depth	-0.498**	rainfall	-0.027	water temp	0.025
Ortho P	light-7 day ave	0.132**	wind-7 day ave	-0.007	wind-7 day ave	0.167
	rainfall	-0.144*	light-7 day ave	0.044	water depth	-0.211
	water temp	0.021	water temp	-0.011	total algae	-0.109
	wind-7 day ave	0.048	total algae	0.027	light-7 day ave	0.291*
	water depth	0.768**	water depth	0.668**		
	wind/samp. day	-0.348**	wind/samp. day	-0.453**	no variation in dependent variable	
Secchi depth	bicarbonate	-0.452**	chlorophyll	-0.226**		
	chlorophyll	-0.440**	carbonate	-0.004		
	carbonate	-0.438**	bicarbonate	-0.230**		

* denotes significance at the .05 level
** denotes significance at the .01 level

Table 15. Correlation coefficients (r) of chlorophyll and twelve estimates of ground, aircraft, and LANDSAT-1 MSS data.

		r			r			r
A.	Band 6	-0.793**	E.	Band 4	0.868**	I.	Band 7	0.631**
	Band 4	-0.786**		Band 6	0.409**		Band 6	0.618**
	Band 5	-0.721**		Band 5	0.326*		Band 4	0.403**
	Band 7	-0.631**		Band 7	-0.027		Band 5	0.399**
B.	Band 4	-0.878**	F.	Band 6	0.846**	J.	IR-R	-0.906**
	Band 6	-0.871**		Band 4	0.836**		BW-IR	0.890**
	Band 5	-0.871**		Band 7	0.831**		IR-G	-0.851**
	Band 7	-0.825**		Band 5	0.778**		BW-G	0.775**
							IR-B	-0.756**
C.	Band 5	-0.355**	G.	Band 7	0.533**	K.	BW-IR	-0.907**
	Band 6	-0.165		Band 6	0.487**		BW-R	-0.827**
	Band 4	-0.143		Band 5	0.313**		BW-G	-0.703**
	Band 7	-0.118		Band 4	0.191			
D.	Band 4	0.599**	H.	Band 4	0.846**	L.	OverR/G	-0.337**
	Band 5	0.541		Band 5	0.809**		Obl R/G	-0.330**
	Band 7	0.430		Band 6	0.801**		OverR/B	-0.321**
	Band 6	0.145		Band 7	0.663**		Hor R/G	-0.313**
							Obl B/G	0.259**

* denotes significance at .05 level
** denotes significance at .01 level

A. LANDSAT-1 uncorrected film density (72 obs.)
B. LANDSAT-1 corrected sensitometry (72 obs.)
C. LANDSAT-1 corrected sensitometry excluding Bitter (54 obs.)
D. LANDSAT-1 corrected sensitometry-Bitter only (18 obs.)
E. LANDSAT-1 corrected for atmosphere-reflected minus received (48 obs.)
F. LANDSAT-1 corrected for atmosphere-least reflective method (72 obs.)
G. Radiation reflected from water-% reflected times incoming (162 obs.)
H. Radiation received by LANDSAT-1 (56 obs.)
I. Percent radiation reflected from water-ground radiometer (160 obs.)
J. Aircraft uncorrected film density (IR-B: color IR/blue filter) (24 obs.)
K. Aircraft corrected sensitometry (34 obs.)
L. Ground photo density ratios (Hor R/G: horizon red/blue ratio) (196 obs.)

Table 16. Correlation coefficients (r) of total algae and twelve estimates of ground, aircraft, and LANDSAT-1 MSS data.

		r			r			r
A.	Band 6	0.615**	E.	Band 4	0.903**	I.	Band 6	0.635**
	Band 4	0.607**		Band 5	0.597**		Band 7	0.594**
	Band 5	0.588**		Band 6	0.589**		Band 4	0.564**
	Band 7	0.369**		Band 7	0.249		Band 5	0.562**
B.	Band 4	0.904**	F.	Band 5	0.923**	J	IR-B	0.694**
	Band 6	0.877**		Band 6	0.918**		BW-G	-0.636**
	Band 5	0.871**		Band 4	0.888**		IR-G	0.526**
	Band 7	0.733**		Band 7	0.842**		IR-V	0.524**
							IR-R	0.309
C.	Band 5	-0.425**	G.	Band 6	0.612**	K.	BW-IR	-0.906**
	Band 6	-0.329*		Band 5	0.549**		BW-R	-0.654**
	Band 7	-0.248		Band 7	0.549**		BW-G	-0.461**
	Band 4	-0.190		Band 4	0.442**			
D.	Band 5	-0.837**	H.	Band 5	0.654**	L.	OverR/G	-0.394**
	Band 4	-0.823**		Band 4	0.635**		Hor R/G	-0.315**
	Band 6	-0.551*		Band 6	0.609**		Obl B/G	0.276**
	Band 7	-0.013		Band 7	0.304*		Hor R/B	-0.275**
							OverB/G	0.237**

* denotes significance at .05 level
** denotes significance at .01 level

A. LANDSAT-1 uncorrected film density (72 obs.)
B. LANDSAT-1 corrected sensitometry (72 obs.)
C. LANDSAT-1 corrected sensitometry excluding Bitter (54 obs.)
D. LANDSAT-1 corrected sensitometry-Bitter only (18 obs.)
E. LANDSAT-1 corrected for atmosphere-reflected minus received (48 obs.)
F. LANDSAT-1 corrected for atmosphere-least reflective method (72 obs.)
G. Radiation reflected from water-% reflected times incoming (162 obs.)
H. Radiation received by LANDSAT-1 (56 obs.)
I. Percent radiation reflected from water-ground radiometer (160 obs.)
J. Aircraft uncorrected film density (IR-B:color IR/blue filter)(24 obs.)
K. Aircraft corrected sensitometry (34 obs.)
L. Ground photo density ratios (Hor R/G:horizon red/blue ratio)(196 obs.)

Table 17. Correlation coefficients (r) of secchi depth and twelve estimates of ground, aircraft, and LANDSAT-1 MSS data.

	r		r		r
A. Band 5	-0.785**	E. Band 4	0.386**	I. Band 5	-0.520**
Band 4	-0.729**	Band 7	0.324*	Band 6	-0.478**
Band 6	-0.657**	Band 6	0.063	Band 4	-0.465**
Band 7	-0.477**	Band 5	0.055	Band 7	-0.382**
B. Band 5	0.711**	F. Band 5	-0.584**	J. IR-B	0.811**
Band 4	0.620**	Band 4	-0.550**	IR-G	0.752**
Band 6	0.562**	Band 6	-0.513**	BW-G	-0.618**
Band 7	0.514**	Band 7	-0.471	IR-R	0.472**
				BW-IR	-0.313
C. Band 5	0.793**	G. Band 5	-0.514**	K. BW-G	0.788**
Band 4	0.680**	Band 6	-0.491**	BW-R	0.754**
Band 6	0.443**	Band 4	-0.436**	BW-IR	0.360*
Band 7	0.288*	Band 7	-0.400**		
D. no variation		H. Band 5	-0.632**	L. OverR/G	0.718**
in		Band 4	-0.606**	OverR/B	0.658**
secchi depth		Band 6	-0.502**	Obl R/G	0.524**
		Band 7	-0.395**	Obl B/G	-0.460**
				Hor R/G	0.458**

* denotes significance at .05 level
** denotes significance at .01 level

A. LANDSAT-1 uncorrected film density (72 obs.)
B. LANDSAT-1 corrected sensitometry (72 obs.)
C. LANDSAT-1 corrected sensitometry excluding Bitter (54 obs.)
D. LANDSAT-1 corrected sensitometry-Bitter only (18 obs.)
E. LANDSAT-1 corrected for atmosphere-reflected minus received (48 obs.)
F. LANDSAT-1 corrected for atmosphere-least reflective method (72 obs.)
G. Radiation reflected from water-% reflected times incoming (162 obs.)
H. Radiation received by LANDSAT-1 (56 obs.)
I. Percent radiation reflected from water-ground radiometer (160 obs.)
J. Aircraft uncorrected film density (IR-B:color IR/blue filter)(24 obs.)
K. Aircraft corrected sensitometry(34 obs.)
L. Ground photo density ratios (Hor R/G:horizon red/blue ratio)(196 obs.)

Table 18. Final regression equations for predicting chlorophyll from the twelve remote-sensing estimates listed in Table 9. (only variables that are significant at the .05 or .01 levels are listed).

	a	b_1	x_1	b_2	x_2	b_3	x_3	b_4	x_4	b_5	x_5
A	105.460	-0.759	Band 6	0.342	Band 7	0.613	Band 5	-0.110	Band 4		
B	481.860	-0.189	Band 4	-0.164	Band 7						
C	-154.910	-0.135	Band 5	0.162	Band 7	0.867	Band 4				
D	932.750	-0.464	Band 4	-0.997	Band 7	0.814	Band 6				
E	-13.036	0.779	Band 4	-0.361	Band 7						
F	1.546	0.203	Band 6	0.306	Band 7	0.156	Band 4	-0.640	Band 5		
G	17.509	0.136	Band 7	-0.939	Band 4	0.143	Band 6	-0.819	Band 5		
H	-37.185	0.104	Band 4	-0.986	Band 7						
I	-1.291	0.431	Band 7	-0.113	Band 5	0.145	Band 6				
J	390.246	-114.183	IR-R	-120.535	BW-G	-53.844	IR-B	44.579	IR-G		
K	367.710	-14.517	BW-IR	-3.540	BW-G						
L	441.329	-151.206	Over R/G	-199.857	Obl R/G						

$Y = a + b_1x_1 + b_2x_2 \ldots + b_nx_n$ where a = y intercept, b = slope, x = remote-sensing data

Table 19. Final regression equations for predicting total algae from the twelve remote-sensing estimates listed in Table 10. (only variables that are significant at the .05 or .01 levels are listed).

	a	b_1	x_1	b_2	x_2	b_3	x_3	b_4	x_4	b_5	x_5
A	19,993	-0.752	Band 6	0.528	Band 7						
B	45,777	-0.680	Band 4	-0.244	Band 6	0.259	Band 7				
C	3,036	-0.203	Band 5								
D	405,021	-0.334	Band 5								
E	-29,441	0.464	Band 4	-0.584	Band 6	0.846	Band 5	-0.511	Band 7		
F	-6,543	0.500	Band 4	0.266	Band 6						
G	-10,296	0.560	Band 6								
H	-16,963	0.117	Band 5	-0.219	Band 7	0.737	Band 6				
I	-13,170	0.386	Band 6								
J	461.8	1.689	IR-B	-11.303	IR-G	-3.655	BW-G	-4.329	IR-R	11.822	IR-V
K	283,525	-13.740	BW-IR								
L	234,051	-116,396	Over R/G	94,651	Over B/G	-259,785	Hor R/G	82,997	Hor R/G		

$Y = a + b_1x_1 + b_2x_2 \ldots + b_nx_n$ where a = y intercept, b = slope, x = remote-sensing data

Table 20. Final regression equations for predicting secchi depth from the twelve remote-sensing estimates listed in Table 10. (only variables that are significant at the .05 or .01 levels are listed).

	a	b_1	x_1	b_2	x_2	b_3	x_3	b_4	x_4	b_5	x_5
A	-0.711	0.576	Band 5	-0.241	Band 7	-0.312	Band 6	0.414	Band 4		
B	-3.106	0.315	Band 5	-0.265	Band 6						
C	-2.489	0.417	Band 5	-0.365	Band 6						
D				no variation in secchi depth							
E	1.083	-0.434	Band 4	0.498	Band 6						
F	1.939	-0.246	Band 5								
G	1.938	-0.105	Band 5	-0.154	Band 6	0.124	Band 7				
H	3.672	-0.302	Band 5	0.574	Band 7	-0.433	Band 4	0.463	Band 6		
I	1.974	-0.241	Band 5	0.153	Band 4	0.182	Band 7	-0.187	Band 6		
J	52,5332	0.490	IR-B	-6.604	BW-G	-19.413	IR-R	-34.817	BW-IR	4.723	IR-G
K	-0.365	0.140	BW-G	-0.675	BW-IR	0.780	BW-R				
L	-13.727	3.334	Over R/G	2.748	Over R/G	1.137	Hor R/G	5.055	Obl B/G	1.782	Obl R/G

$Y = a + b_1x_1 + b_2x_2 \ldots + b_nx_n$ where a = y intercept, b = slope, x = remote-sensing data